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A procedure for extracting information from a heart sound signal.

The invention relates to the extraction and classification of information in phonocardigraphic signals in order to aid evaluation and diagnosis of heart conditions. The invention furthermore relates to techniques forming part of such extraction.

Signals obtained by means of a transducer are phonocardiographic representations of sounds traditionally listened to by means of a stethoscope. Training in auscultation takes a long time and requires an aptitude for recognising and classifying aural cues, frequently in a noisy environment. 20-30 different conditions may need to be differentiated, and within each, the severity evaluated. Furthermore, there may be combinations among these. These factors contribute to explaining why not all physicians perform equally well when diagnosing heart conditions, and why it may be time-consuming.

The so-called first (S1) and second (S2) heart sound are very important markers in the assessment of a heart sound signal. These sounds are directly related to the functioning of the heart valves, in that S1 is caused by the closure of the atrioventricular valves and contraction of the ventricles and S2 is caused by the closure of the aortic and pulmonary valves.

A number of patents relate to the extraction of the S1 and S2 signals, such as US 6,048,319, which concerns the measurement of the time interval between the S1 and S2 signals in relation to the heart rate in order to determine the degree of coronary artery disease. The measurement is based on peak detection and autocorrelation and it may be considered a relatively slow process.

According to the present invention the detection of S1 and S2 is obtained by performing the steps of feature extraction and classification based on the energy distribution over time in a feature time function. The feature extraction is performed by the steps of bandpass filtering, followed by instantaneous power and lowpass

filtering. This generates a series of signal peaks or "hills", each relating to either an S1 or an S2, and a signal classification step determines which "hill" is to be regarded as either an S1 or an S2, whereby a systole is correctly identified.

A different category of signals related to various heart conditions is generally known as murmurs. The known procedures of isolating and categorizing murmurs are generally dependent on the simultaneous recording of electrocardiographic data, such as US 5,957,866 and US 6,050,950 and this complicates the practical use of auscultation techniques considerably.

The above solutions are very complex and rely on techniques that are equivalent to a long averaging time. According to the invention a method has been derived which is more precise and obtains a faster result. This is obtained by a sequence of steps, comprising an optional adaptive noise reduction, detection of S1 and S2, e.g. by means of the feature extraction procedure mentioned above, enhancement of the signal by elimination of the S1 and S2 contributions, performing spectral analysis and feature enhancement in order to obtain the energy content present in areas of a time-frequency representation delimited by frequency band times time interval in the form of energy distributions, classifying the energy distributions according to pre-defined criteria, and comparing the energy distributions to a catalogue of distributions related to known medical conditions and extracting information by comparing the enhanced signal to stored time functions.

The correct placement in time of S1 and S2 permits the energy relating to these sounds to be eliminated in the signal processing, and the resulting sound (including murmurs, etc.) is a useful starting signal for further analysis, because it increases the dynamic range of the remaining signal.

Diagnostic classification and evaluation is obtained by identifying specific features in order to extract characteristic patterns which are compared to a library of patterns typical of various kinds of heart disorder, and the closeness of the measured signal to these patterns.

The invention will be more fully described in the following with reference to the drawing, in which

Fig. 1 shows a functional block diagram of the complete information extraction process according to the invention,
Fig. 2 shows the structure providing the first analysis of the heart signal,
Fig. 3 shows an original heart signal and its corresponding spectrogram,
Fig. 4 shows the spectrogram of a bandpass filtered heart signal,
Fig. 5 shows the result of a time marginal distribution of the energy,
Fig. 6 shows the identification of large and small "hills" in the feature, and
Fig. 7 shows the identification of S1 and S2 irrespective of relative power.

In Fig. 1 is seen a functional block diagram of the procedure and sub-procedures according to the invention. The following description relates to a practical example of an embodiment according to the invention.

The input for the procedure consists of 8 seconds of heart sound signal, sampled at a rate of 1000 Hz and read into a digital register subsequent to A/D conversion.

The detector for S1 and S2 essentially consists of two separate algorithms, a feature extraction part and a classification part. The purpose of the feature extraction is to transform the input signal to a domain, in which the respective location in time of S1 and S2 is more distinct than in the original signal. The classification part determines the precise location of S1 and S2 and correctly identifies them as such.

In Fig. 2 is demonstrated how murmurs may be observed in the spectrogram of a time function of an original heart sound. The spectrogram is obtained by Fast Fourier Transform. The first and second heart sounds S1 and S2 have only a low-frequency content compared to the broad-band nature of the murmurs, and for this reason the signal is band-pass filtered by convolution of the original signal with the impulse response function of a bandpass filter. The corresponding spectrogram is shown in Fig. 3, in which peaks of higher energy are visible but not clearly identifiable. In order to obtain a time function of the occurence of these higher energies, the time marginal distribution of the spectrogram is performed according to Eq. (1):

$$F_x(t, \omega) = \left|\int x(\tau) g(t-\tau) e^{-j\omega\tau}\right|^2$$

Hereby a "final feature" is obtained as a time function as shown in Fig. 5. In essence, this time function is obtained by bandpass filtering, instantaneous power extraction and lowpass filtering. It is now clear that the "final feature" displays a "hill" every time an S1 or S2 occurs in the heart signal.

As the magnitudes of the "hills" corresponding to S1 and S2 are comparable, it is necessary to distinguish between them by applying classification rules. First all "hills" in the "final feature" must be identified. This is obtained for all samples of the time function which fulfil the following criteria:

feature(k-1) < feature (k) <u>and</u> feature(k) > feature (k+1).

The next step is to construct a table of possible systoles. A systole is a pair of "hills" (S1 and S2) constrained by the time distançe between the "hills". The time distance must fall within the following limits:

230 ms < T < 500ms for human hearts.

The final sequences of systoles is determined by finding the sequence of systoles in the table having maximum energy that fulfil the following constraints:

- systole time deviation < 18%
- time between systoles (diastole) > 0.9 times systole time
- amplitude deviation of S1 < 500%
- amplitude deviation of S2 < 500%
- in the case of overlapping systoles, the systole with maximum energy must be selected.

The result of the identification is displayed in Fig. 7, in which a fat black line to the top of a "hill" indicates the time position of a first heart sound S1 and a thin black line a second heart sound S2.

With the time positions of the first (S1) and second (S2) heart sounds correctly detected in the signal (given as sample numbers, corresponding to positions measured in milliseconds) it is now possible to evaluate the much weaker sounds, the heart murmurs. In the following, these detected time positions will be referred to as S1 markers and S2 markers, respectively. Reference is again made to Fig. 1.

Delimitation of Systoles and Diastoles

Only the systole and diastole parts of the heart sound signal are used for the murmur detection. All periods, beginning 50 milliseconds after an S1 marker and ending 50 milliseconds before the immediately following S2 marker, are defined as systoles.

Correspondingly, all periods, beginning 50 milliseconds after an S2 marker and ending 50 milliseconds before the immediately following S1 marker, are defined as diastoles. This is a primitive but efficient manner of eliminating the influence of the very energetic first and second heart sounds. At a later stage in the performance of the procedure some corrections are made (*vide* below), but it may be more advantageous to perform the elimination using more refined approaches at this early stage in the procedure.

Time and Frequency Decomposition of Systoles and Diastoles

The sound energy content in the sound signal is calculated by means of a spectrogram based on the Discrete Fourier Transform (DFT) using a vector length which is a power of 2, such as 16. In order to be able to classify murmurs regarding frequency contents and time distribution, each systole and diastole is decomposed into 14 frequency bands and 10 time slices, the two lowest frequency bands being discarded. The 14 frequency bands cover the frequency range from 62.5 Hz to 500 Hz, each having a width of 31.25 Hz.

Before the calculation of the spectrogram, the sound signal is differentiated twice (corresponding to a high-pass filtration) in order to take into account the frequency

characteristics of the human hearing, being more sensitive to higher than lower frequencies within the frequency range in question.

It is considered that a parallel bank of band pass filters will perform faster in the present environment.

The 10 time slices for a given systole or diastole all have the same width, corresponding to 1/10 of the total length of the systole/diastole.

The combination of frequency bands and time slices creates a 14x10 matrix for each systole/diastole. For each element in these matrices, the energy content is divided by the width of the relevant time slice, thus yielding matrices containing the heart sound power (energy per time) for the 140 time/frequency elements of each systole/diastole.

Definition of Standard Systoles and Diastoles for Each Frequency Band

The matrices for each systole are combined to a single 14x10 systole (S) matrix by median filtration:

For each combination of a frequency range and a time slice, the power values from the different systoles are compared, and the median value is chosen to be the standard value. This is an efficient way of obtaining a stable value. Thus, for each of the 14 frequency bands (rows in the matrix), 10 standard power values combine to a standard systole.

The diastole matrices are combined to a D matrix in the same way.

Extraction of Power and Frequency Feature Vectors

A systole power (SP) vector with 10 elements is constructed by summing the 14 standard power values for each of the 10 time slices. Thus, the SP vector consists of the column sums for the S matrix.

A diastole power vector (DP) is constructed in the same way.

A systole mean frequency (SMF) vector (also with 10 elements) is calculated by weighting the power value for each frequency band with the mean frequency of the corresponding band, summing the 14 results, and dividing the sum with the corresponding element in the SP vector.

Correspondingly, a diastole mean frequency (DMF) vector is calculated.

Correction of Feature Vectors for S1/S2 Remnants

Due to the very simple definition of systoles and diastoles, the first and/or last tenths of some of the systoles and diastoles may be "contaminated" with parts of S1 or S2. Typically, this is manifested by larger values of the first/last elements in SP/DP and lower values of the corresponding elements in SMF/DMF, because of the high power and the relatively low frequencies of S1 and S2 compared to the murmurs in systoles and diastoles.

Therefore, the beginning and end of the SP, SMF, DP, and DMF vectors are examined and corrected if necessary in dependence of the following relationships:

If $SMF(2) - SMF(1) > 2*|SMF(3) - SMF(2)|$ or
$SP(1) - SP(2) > 2*|SP(2) - SP(3)|$,
$SP(1) == SP(2)$ and $SMF(1) == SMF(2)$.

If $SMF(9) - SMF(10) > 2*|SMF(8) - SMF(9)|$ or
$SP(10) - SP(9) > 2*|SP(9) - SP(8)|$,
$SP(10) == SP(9)$ and $SMF(10) == SMF(9)$.

Corresponding examinations and corrections are performed for DP and DMF.

Creation of Murmur Intensity Vectors

The elements in a systole intensity (SI) vector is created from the elements in the SP vector in the following way using absolute values:

$\log 10(SP(x)) \leq -1.25$	$SI(x) = 0$
$-1.25 < \log 10(SP(x)) \leq -0.80$	$SI(x) = 1$
$-0.80 < \log 10(SP(x)) \leq -0.35$	$SI(x) = 2$
$-0.35 < \log 10(SP(x)) \leq +0.10$	$SI(x) = 3$
$+0.10 < \log 10(SP(x)) \leq +0.55$	$SI(x) = 4$
$+0.55 < \log 10(SP(x)) \leq +1.00$	$SI(x) = 5$
$+1.00 < \log 10(SP(x))$	$SI(x) = 6$

A diastole intensity (DI) vector is constructed in the same way.

It may be relevant to use values relative to e.g. the intensity of S1 and/or S2, in which case the logarithmic conversion may use other limits than given above.

Correction of Murmur Intentity Vectors for Noise

In order to correct for transient noise signals, the following corrections are performed:

SI(1) is set to 0, if SI(2) is 0
SI(10) is set to 0, if SI(9) is 0

If any element in SI is more than 1 larger than both of its neighbours, the element is set to be equal to the highest of the neighbours.

Similar corrections are performed for DI.

Classification of the Intensity of Murmurs

The intensities of any systolic and/or diastolic murmur is defined as being the maximum value of SI and/or DI, resp.

If the maximum values are both 0, the heart sound is classified as containing no murmurs.

Classification of the Time Distribution of Murmurs

If at least one of the maximum values found is larger than 0, the systolic and/or diastolic murmurs are classified according to the profiles of SI and DI, resp.

Any systolic murmur is classified within the first class in the list below whose description matches the content of SI:

Systolic ejection murmurs:	The values in SI are increasing to a certain point and decreasing after that point. Steps that are neither in- or decreasing are allowed within the increasing as well as the decreasing part of the vector.
Early systolic murmurs:	The last five values in SI are all 0.
Early-mid systolic murmurs:	The last three values in SI are all 0.
Late systolic murmurs:	The first five values in SI are all 0.
Mid-late systolic murmurs:	The first three values in SI are all 0.
Pansystolic murmurs:	The SI vector does not match any of the above descriptions.

Any diastolic murmur is classified within the first class in the list below whose description matches the content of DI:

Decreasing diastolic murmurs:	The values in DI are decreasing, but never increasing. Steps that are neither in- or decreasing are allowed.
Diastolic murmurs with pre-systolic accentuation:	DI(9) > DI(8) and DI(10) > DI(9).
Uniform diastolic murmurs:	The DI vector does not match any of the above descriptions.

Classification of the Frequency Range of Murmurs

Systolic and diastolic murmur frequencies are classified according to the frequency band containing the largest power value in the tenth(s) of the systole/diastole corresponding to the found maximum values of SI/DI.

If the largest power value is found in one of the two lowest frequency bands (containing frequencies below 125 Hz), the murmur is classified as a low-frequency murmur.

If the largest power value is found in one of the eight highest frequency bands (containing frequencies above 250 Hz), the murmur is classified as a high-frequency murmur.

If the none of the above is the case, the murmur is classified as a medium-frequency murmur.

Output from the Murmur Detection Algorithm

The output from the algorithm is either a string describing the found murmur(s) or three values for each found murmur coding for the intensity, the time distribution and the frequency range of the murmur(s).

It will be noted that in the above description of a specific embodiment that apparently arbitrary steps were introduced of double differentiation and of applying a logarithmic function in order to obtain intensity values. These steps have a psychoacoustic foundation related too the hearing of the auscultating person. It is obvious that the classification may well proceed without these steps, however it has been determined in practical use that the classifications obtained by applying these steps are commensurate with observations made by trained medical staff, and that the results thereby obtained are much more directly applicable to the auscultated phenomena at hand. In this way the medical professional will be much further aided than by mere reading and comparing sets of three values.

It will be understood that once the signal has been converted to digital representation of data, its manipulation may take place in dedicated processors, RISC processors or general purpose computers, the outcome of the manipulation being solely dependent on the instructions performed on the data under the control of the program written for the processor in order to obtain the function. The physical location of the data at any one instant (i.e. in varying degrees of processing) may or not be related to a particular block in the block diagram, but the representation of the invention in the form of interconnected functional blocks provides the skilled person with sufficient information to obtain the advantages of the invention.

The foregoing description of the specific embodiments will so fully reveal the general nature of the present invention that others skilled in the art can, by applying current knowledge, readily modify or adapt for various applications such specific embodiments without undue experimentation and without departing from the generic concept, and therefore, such adaptations and modifications should and are intended to be comprehended within the meaning and range of equivalents of the disclosed embodiments. It is to be understood that the phraseology or terminology employed herein is for the purpose of description and not of limitation. The means, materials,

and steps for carrying out various disclosed functions may take a variety of forms without departing from the invention.

Thus, the expressions "means to ... " and "means for ...", or any method step language, as may be found in the specification above and/or in the claims below, followed by a functional statement, are intended to define and cover whatever structural, physical, chemical, or electrical element or structure, or whatever method step, which may now or in the future exist which carries out the recited functions, whether or not precisely equivalent to the embodiment or embodiments disclosed in the specification above, i.e., other means or steps for carrying out the same function can be used; and it is intended that such expressions be given their broadest interpretation.

PATENT CLAIMS

1. A procedure for extracting information from a phonocardiographic signal obtained from a transducer and subjected to signal processing, including identification of characteristic signal components,

characterised in that it comprises the following steps:

- extracting the first and second heart sounds by classification according to energy levels,
- eliminating the contribution of the said first and second heart sounds from the signal,
- performing spectral analysis and feature enhancement in order to obtain the energy content present in areas of a time-frequency representation delimited by frequency band times time interval in the form of energy distributions
- classifying the energy distributions according to pre-defined criteria
- comparing the energy distributions to a catalogue of distributions related to known medical conditions.

2. A procedure for extracting information from a phonocardiographic signal according to claim 1, characterised in that first and second heart sounds are detected and placed correctly on a time axis by performing the steps of feature extraction and classification based on the energy distribution over time in a feature time function by the steps of bandpass filtering, followed by instantaneous power and lowpass filtering of the original phonocardiographic signal.

3. A procedure for extracting murmur information,

characterised in that it comprises the following steps:

- obtaining a digital representation of heart sound for a predetermined number of seconds,
- extracting the first and second heart sounds by classification according to energy levels,
- identifying the time of occurence of the first and second heart sounds in each cycle,
- windowing the parts of heart sounds falling between the first and second heart sounds, and second and first heart sounds, respectively
- decomposition of the signals into a predetermined first number n1 of frequency

bands, each band being decomposed into a predetermined second number n2 of time-slices

- obtaining a systole (SP) and a diastole (DP) power vector consisting of the sum of n1 powers measured in each of the n2 time slices
- obtaining a systole (SMF) and a diastole (DMF) mean frequency vector by weighting the power value for each of n1 frequency bands with the mean frequency of the corresponding band, summing the results and dividing the sum by the corresponding element in the respective systole or diastole power vector
- while using the time of occurence of the intensity vectors of the various classes for classifying the time distribution of murmurs.

4. A procedure for extracting murmur information according to claim 3, characterised in that it comprises the following step subsequent to decomposition into n1 frequency bands and n2 time-slices,

- for each combination of a frequency band and a time slice, the power values from the different systoles are compared, and the median value is chosen to be the standard value for a power vector.

5. A procedure for extracting murmur information according to claim 3, characterised in that a step preceding the step of obtaining systole and diastole murmur intensity vectors SI and DI consists of refining the windowing by setting the values of SP, DP, SMF, and DMF of the first or last elements equal to the second or last-by-one values, respectively, if the values of the first or last elements of the corresponding vectors fulfil predetermined deviation criteria.

6. A procedure according to claim 3, characterised in that further steps are included in the procedure, comprising

- subjecting the signal to double differentiation before decomposition
- obtaining a systole (SI) and diastole (DI) murmur intensity vector, respectively, by taking the logarithm of the corresponding SP and DP vectors,
- classifying the obtained logarithmic vectors into murmur intensity classes
- comparing the energy distributions to a catalogue of distributions related to known medical conditions.

ABSTRACT

The invention relates to a procedure for extracting features from phonocardiographic signal's without the use of synchronizing information from electrocardiographic signals. The features extracted are the timing and value of first and second heart sounds and various combinations of timing and value of signal components constituting heart murmur. Such combinations are directly related to various heart conditions, which are more easily diagnoseable by a medically trained person when assisted by the signal extraction according to the invention. The features are extracted by a novel combination of energy/time relationships for for the heart signal and various novel classification schemes.

1/3

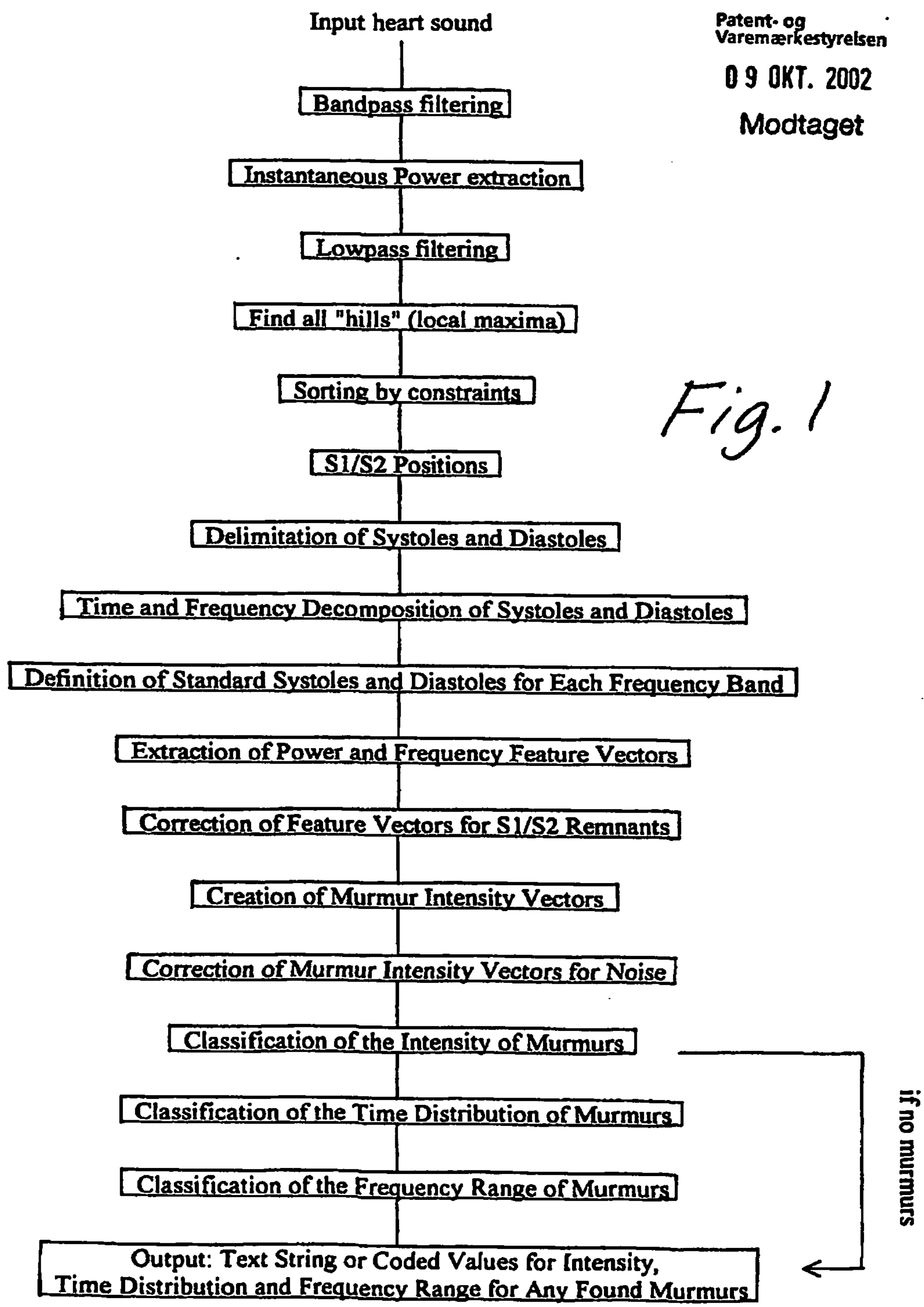

Input heart sound
Bandpass filtering
Instantaneous Power extraction
Lowpass filtering
Find all "hills" (local maxima)
Sorting by constraints
S1/S2 Positions
Delimitation of Systoles and Diastoles
Time and Frequency Decomposition of Systoles and Diastoles
Definition of Standard Systoles and Diastoles for Each Frequency Band
Extraction of Power and Frequency Feature Vectors
Correction of Feature Vectors for S1/S2 Remnants
Creation of Murmur Intensity Vectors
Correction of Murmur Intensity Vectors for Noise
Classification of the Intensity of Murmurs
Classification of the Time Distribution of Murmurs
Classification of the Frequency Range of Murmurs
Output: Text String or Coded Values for Intensity, Time Distribution and Frequency Range for Any Found Murmurs
if no murmurs

Fig. 1

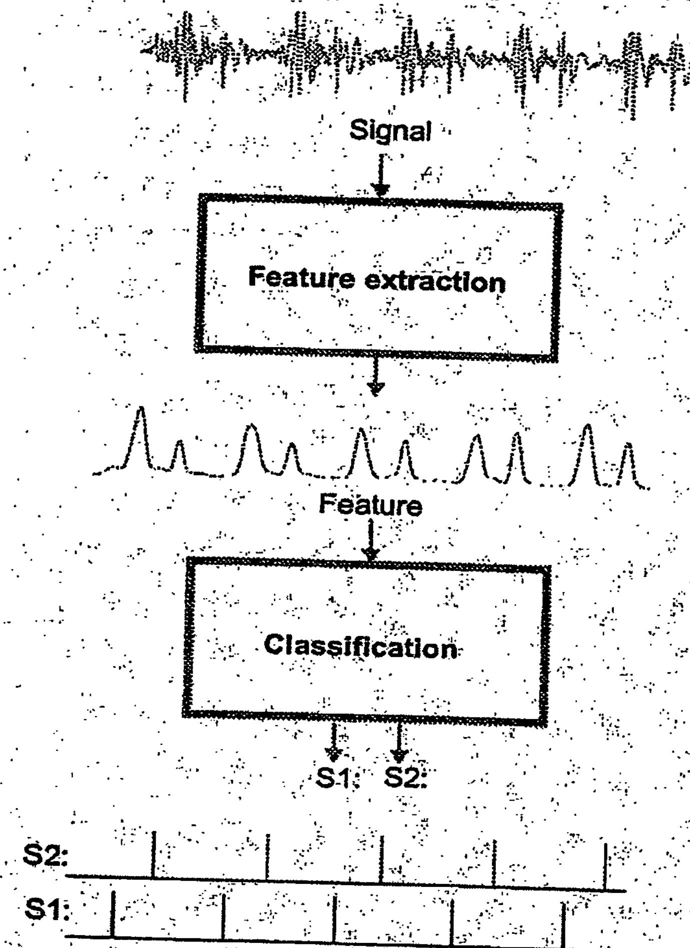
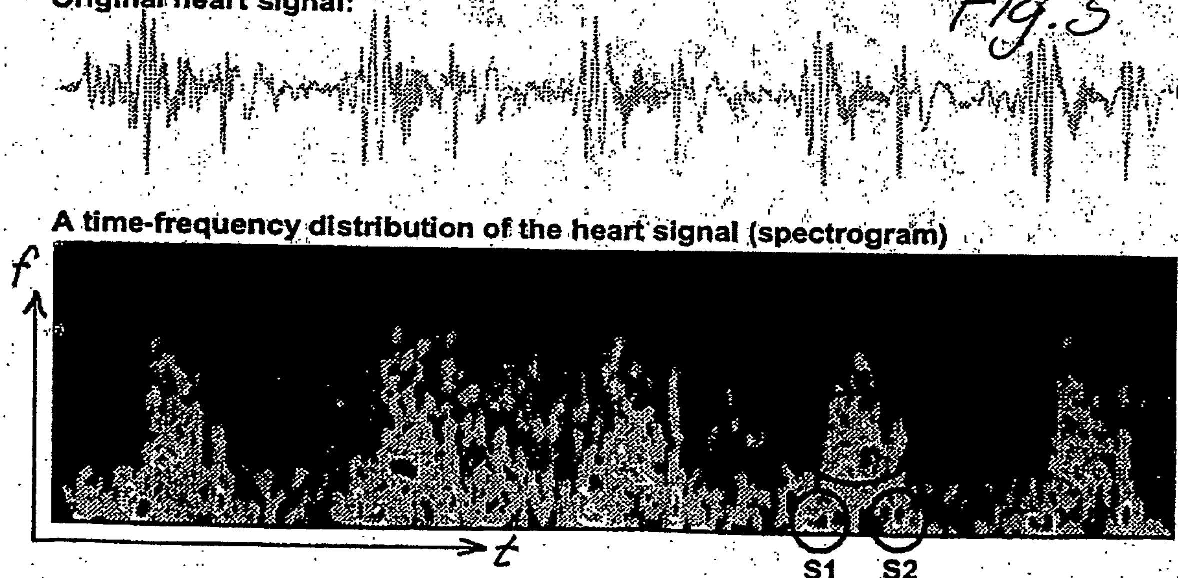


Fig. 2

Original heart signal:



A time-frequency distribution of the heart signal (spectrogram)

Fig. 3

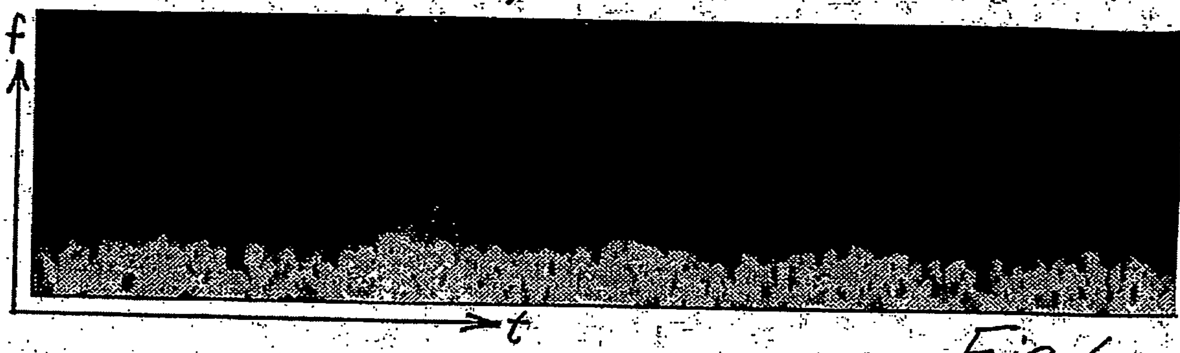


Fig. 4

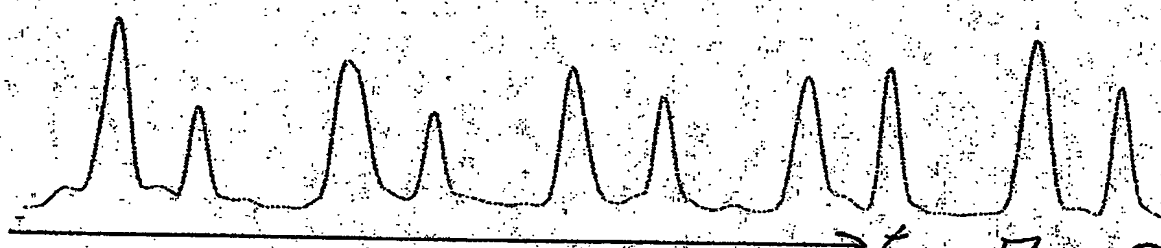


Fig. 5

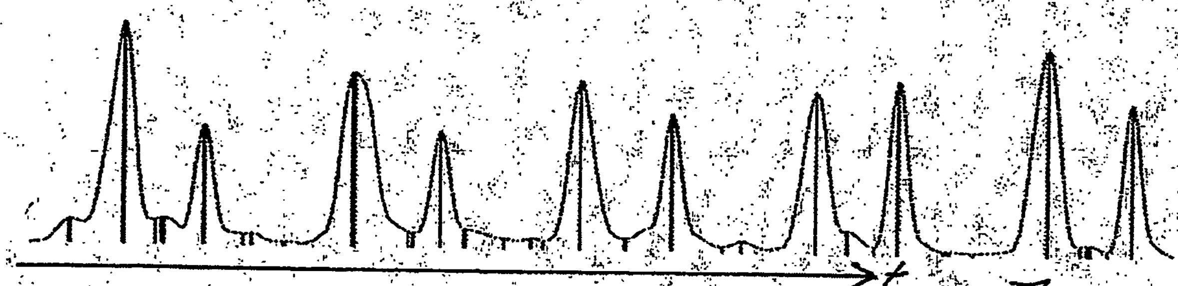


Fig. 6

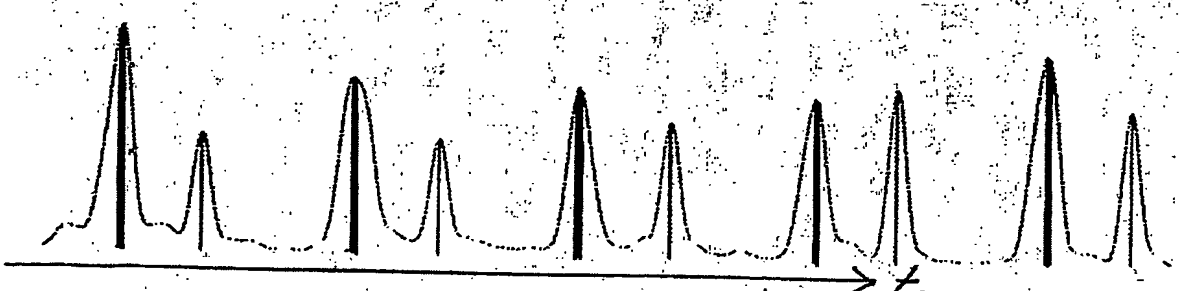


Fig. 7